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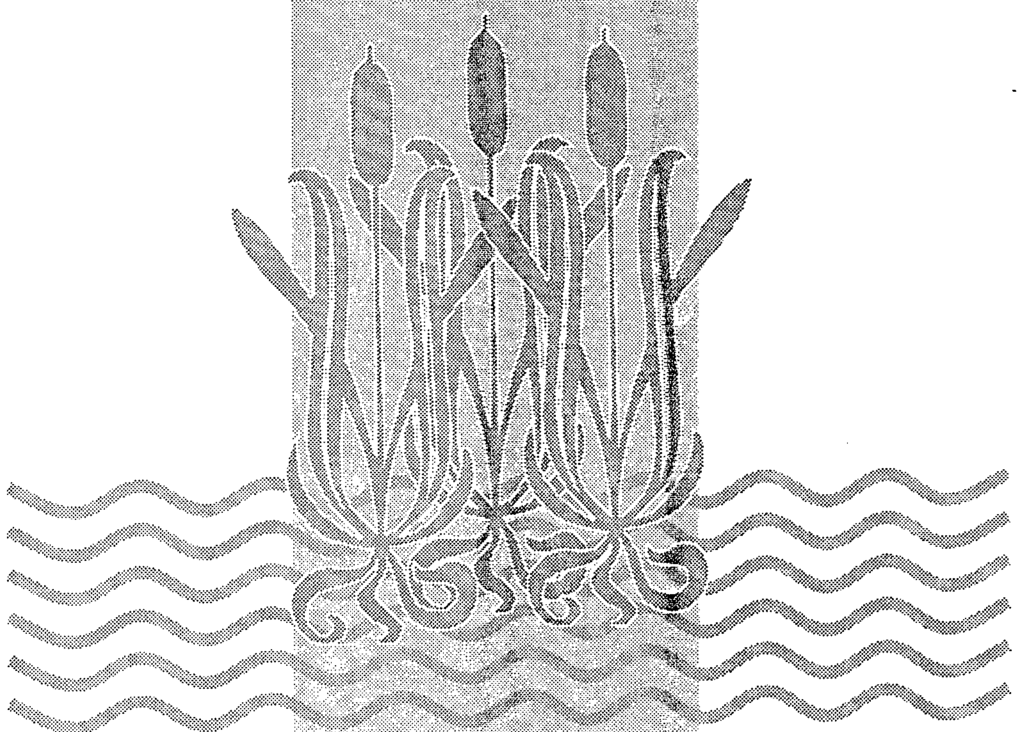
HYDROLOGIC BUDGET FOR A WETLAND SYSTEM



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16. Abstract

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Empirical estimation of wetland *ET* revealed that the Penman method most closely reflected actual wetland *ET*, the Thornthwaite method predicted water loss at a rate significantly less than the actual rate, and restrictions of the Class A pan evaporation method rendered the method inappropriate for the given conditions. The accuracy of any empirical estimator to reflect *ET* rates may improve from on-site data collection of climate parameters.

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

An important functional indicator of the success of a constructed wetland as a replacement for a natural system is the hydrology of a site and whether it is adequate to support wetland vegetation and habitats. For constructed wetlands with potentially limiting hydrologic conditions, such as sites that rely on stormwater runoff as the primary source of water, particular attention to water loss through evapotranspiration (*ET*) is necessary in determining the water balance. The literature reveals a variety of techniques used to calculate *ET* and demonstrates the difficulty in estimating *ET*. Of the methods presented in this report, three empirical relationships were applied to the water balance of a stormwater-supported mitigated wetland. The results were compared to those given by direct measurement.

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INTRODUCTION

Section 404 of the Clean Water Act mandates that when any highway construction activity results in the fill of natural wetlands, the agency responsible must compensate for displacing the natural system by creating an artificial wetland. A mitigated wetland is a type of constructed wetland created specifically to replace natural systems that were filled during development. The U.S. Environmental Protection Agency (EPA) charged the U.S. Army Corps of Engineers (COE) with monitoring compliance with provisions of the Clean Water Act. The Virginia Department of Transportation (VDOT) must, therefore, demonstrate to COE that displaced systems have been adequately replaced by constructed wetlands.

This task is complicated by several factors. Guidelines for wetland delineation are vague because of the broad spectrum of wetland classification. For example, the term *wetlands* can encompass bogs, marshes, mires, fens, swamps, and other wet ecosystems. Wetlands in general can be described as combinations of terrestrial and aquatic systems with the presence of three components: water, unique soil that differs from that of adjacent uplands, and hydrophytic vegetation (Mitsch & Gosselink, 1986). Federal regulations are not entirely specific and describe wetlands in the Clean Water Act as:

> Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas (U.S. EPA, 1994, p. 50).

In terms of hydrologic conditions, wetland delineation is limited to areas that are inundated or saturated for at least 1 week during the growing season under average conditions. Since flooding events do not have a significant effect on dormant trees in the winter, observations of water inundation during the non-growing season are not considered in deciding whether a site meets wetland hydrology criteria according to federal requirements. When hydrologic data are not available, site classification is often based on soils and vegetation, where soils must be saturated to the surface and the canopy, subcanopy, and ground cover strata are given equal weight (Light, Darst, MacLaughlin & Sprecher, 1993).

A significant motivation for federal protection of wetlands is to maintain unique ecological niches that create habitats for many plants and animals, including some endangered species. Further, wetlands protect human resources by providing flood control and storage and reduce peak flows during storm events to prevent inundation downstream (Soil Conservation Service, 1992). The water quality benefits enhance downstream aesthetics and control potentially harmful discharges. Wetlands have a natural ability to reduce levels of many forms of pollutants, including, but not limited to, nitrogen, phosphorus, heavy metals, and suspended solids. Conversely, wetlands can act as exporters of transformed nutrients to downstream ecosystems (Yu, Fitch, Earles & Kaighn, 1997). For this reason, the Virginia Department of Transportation (VDOT) investigated the use of constructed wetlands as a best management practice (BMP) to treat highway stormwater runoff (Yu et al., 1997).

Constructed wetlands are generally built with water control structures, such as berms, dikes, weirs, or vegetated spillways, to prevent excessive water losses from surface outflow. These types of design considerations can render a constructed site more effective than a natural site in terms of both flood control and water quality benefits. For example, natural systems are sometimes overwhelmed during flooding events, whereas retention times can be controlled and excess quantities (outflow) released more slowly if proper attention is given to calculating the drainage area and, therefore, to sizing constructed sites and including control devices (Yu, Fitch, Earles & Fassman, 1998).

The success of a constructed or mitigated wetland depends in large part on the hydrologic conditions. Resistance to flow caused by the vegetation and the physical layout of the site, combined with the volume of storage available, provides the means for peak attenuation and dissipation of runoff momentum during storm events. The water quality benefits of wetlands are obtained through a combination of physical, chemical, and biological processes, which are almost all dependent on the movement of water through the system and the amount of water present. Hydrologic conditions of the site not only largely define wetlands but also provide the means for a wetland, natural or constructed, to perform any of the desired functions (Garbisch, 1994; Hammer & Kadlec, 1986; Kadlec, 1990).

Since site hydrology serves as an important functional indicator of wetland performance, one of the parameters for which COE requires data concerns the water budget. Figure 1 shows the components of a wetland hydrologic budget. In basic terms, the water budget relates the difference between all gains of water into the system and all losses of water from the system with the change in storage. Gains include events such as precipitation and inflow from a stream, stormwater runoff, and groundwater supplies. Water is lost through surface outflow, groundwater recharge, and evapotranspiration (*ET*).

ET can be a significant source of water loss, but no consensus exists as to the best method for its calculation. A literature review revealed that few *ET* estimators have been determined specifically for wetland systems, and those that are available are often

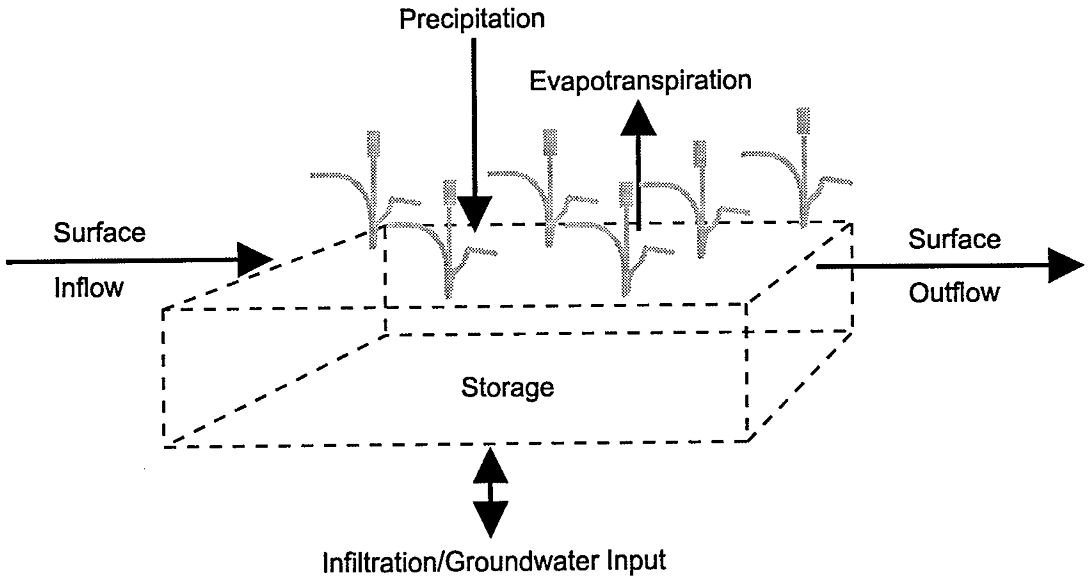

Figure 1. Wetland Water Balance

determined on a much larger spatial scale than applies to many of VDOT's mitigation sites. *ET* is also highly dependent on local climate conditions. Other significant factors in determining *ET* rates are the time scale under consideration and the availability of data.

PURPOSE AND SCOPE

This study was performed to examine the hydrologic budget of a mitigated wetland with a focus on estimating *ET* losses using several methods and comparing them, as suggested by the National Cooperative Highway Research Program (1997). The findings of a similar VDOT study of wetland water balances (Daniels, Persaud, Fomchenko, Spieran, Focazio & Fitch, 1997) are currently under review.

The objectives of this study were:

1. To conduct a literature review of *ET* studies.
2. To examine and compare different methods of estimating *ET*.
3. To compute the hydrologic budget for a constructed wetland using selected methods.
4. To recommend the most suitable method or methods of *ET* estimation for VDOT to employ in future applications.

Research objectives were addressed by examining the water balance of the Rte. 288 mitigation site in Chesterfield County, Virginia, from September 6, 1997, to October 27, 1997. Since VDOT is concerned with fulfilling COE requirements, attempts to determine the quantity of water within a wetland system, where an abundance of water is considered "good," focuses attention on potential cases of maximum water loss from the system. In other words, does the mitigation site satisfy the hydrologic requirements of COE to classify as a wetland in the worst case scenario of maximum water losses? With this in mind, four methods of calculating *ET* were selected and applied to the mitigation site.

METHODS

Literature Review

The literature review was performed by examining journal publications, text books, conference proceedings, and publications of the Virginia Transportation Research Council. Sources were identified mainly by keyword searches in the University of Virginia's online library catalog on the Virgo system.

Selecting Methods to Estimate *ET*

Four methods for estimating water loss attributable to *ET* were selected based on prevalence in the literature and available data.

Computing the Hydrologic Budget for a Constructed Wetland

Site

The site chosen for examination is a 2.02-ha mitigated wetland in the median of Rte. 288, a four-lane highway in Chesterfield County, Virginia. Three inlets and one outlet conduct stormwater runoff from Rte. 288 (28,000 vehicle ADT, 1996) through the wetland. Figure 2 shows the site layout.

The site is heterogeneous in terms of vegetative cover. Figure 2 provides an example of the variety of vegetation. It is characterized by a combination of wet meadow, fresh marsh, and tree swamp area, with a large open water zone near the outlet. Between midspring and late fall of 1996, more than 24 plant species were present, and square meter counts indicated a vegetation density ranging from moderate to abundant. Details of vegetation data are available elsewhere (Yu et al., 1998). The open water fraction comprises approximately 25 percent of the entire site. Although some dry areas exist, soil conditions are mainly saturated, evidenced by shallow standing water (2.5 to 10

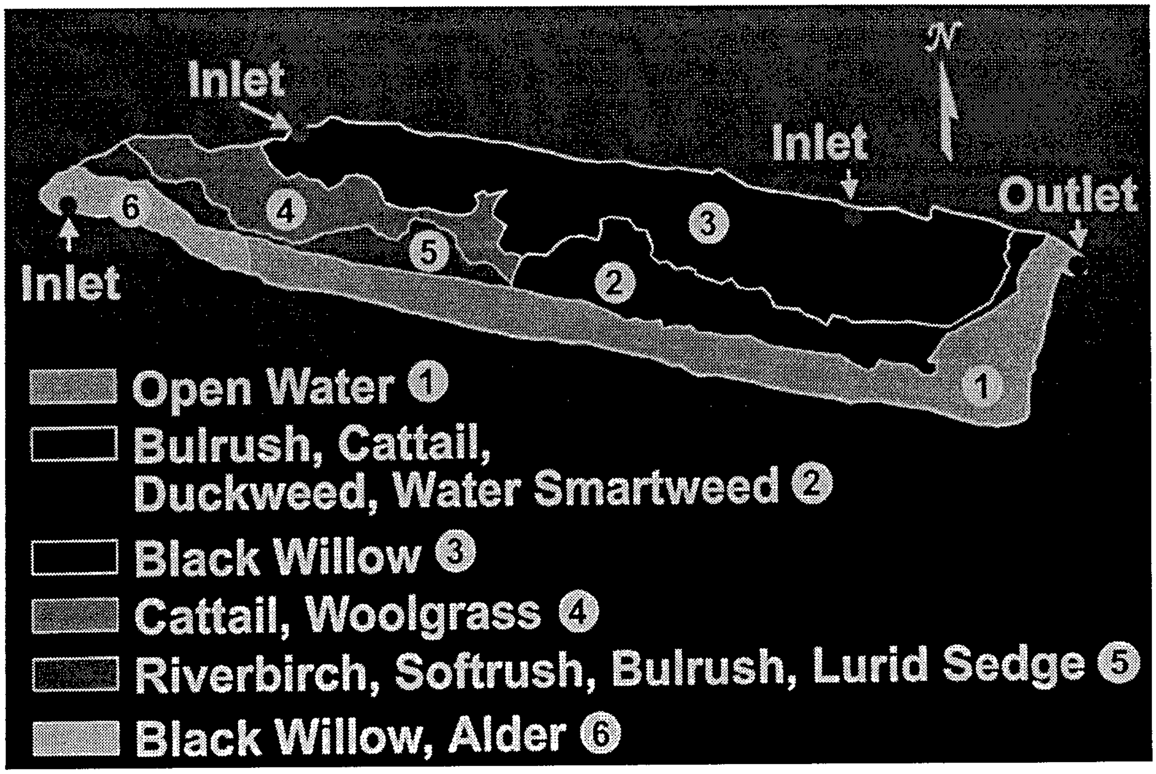

Figure 2. Site Layout and Delineation of Dominant Vegetation

cm) covering most of the site. The beaver dam blocking the outlet of the wetland created an open water pool with depths up to approximately 1 m.

Inlets

Inlets 1 and 2 are at the west end of the site next to the westbound and eastbound lanes of the highway, respectively. Flow entering the wetland through these inlets must travel the entire length of the site before reaching the outlet at the east end. A 0.91-m rectangular weir in a concrete channel facilitates flow measurements at the monitoring station at inlet 1. Rain is collected by a tipping bucket rain gage at this inlet. Figure 3 shows the rain gage and weir structure at inlet 1.

Flow entering the wetland via a 1.07-m circular concrete pipe at inlet 2 is calculated using the Manning equation with a roughness factor of 0.015. A 90° V-notch weir controls flow through a 0.38-m plastic corrugated pipe at inlet 3. Runoff entering the wetland through inlet 3 on the bank of the westbound lane is short circuited around most of the wetland because of its proximity to the outlet (approximately 18 m). Maximum potential water quality benefits are not realized by stormwater conducted to the wetland via inlet 3 because of the short circuiting, but the magnitude of flow through this inlet is small compared to the contributions of the other inlets; therefore, overall stormwater treatment is still significant (Yu et al., 1997).

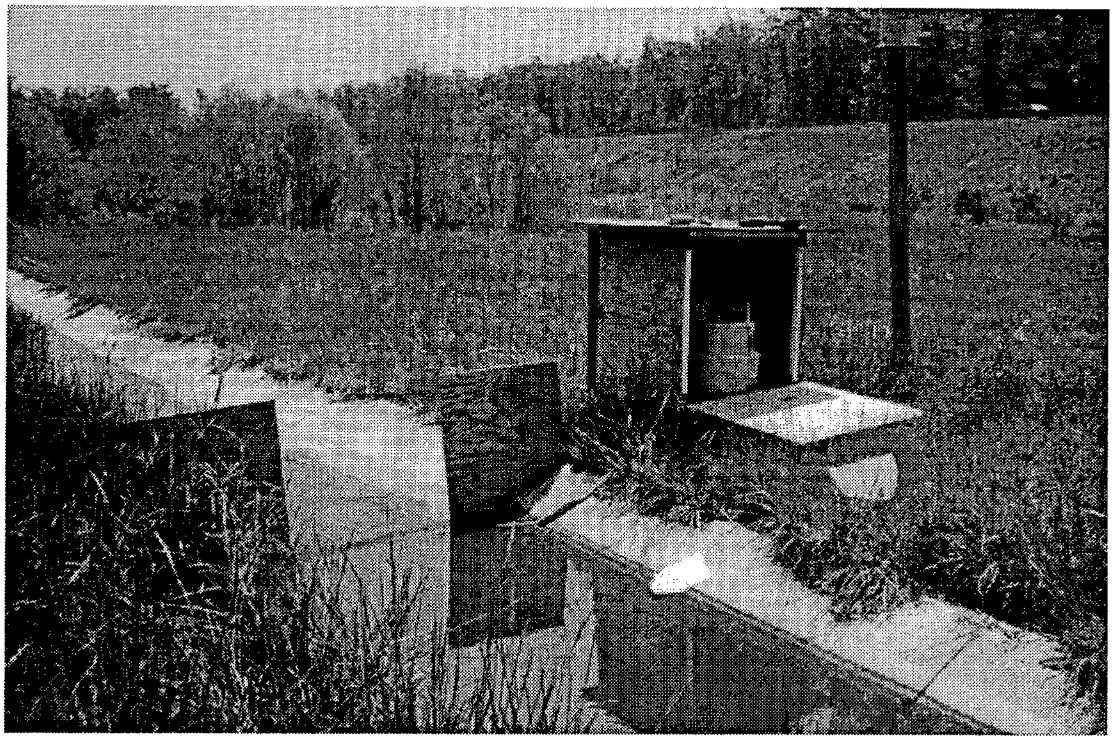

Figure 3. Inlet 1 Monitoring Station

Outlet

Since the natural outlet to the wetland is blocked by a beaver dam, the research team constructed a pond leveler for outlet control in the summer of 1997. Water exits the wetland through an 0.2-m-diameter PVC pipe, which runs under the beaver dam as shown in Figure 4. A 90° elbow was later added to serve as a standpipe to help regulate the pond level. In general, flow through the wetland is linear with an aspect (length:width) ratio of 4:1 and an average residence time of 27.9 hours.

Although flow through all of the inlets is calculated directly by SIGMA 900MAX automatic samplers installed at each station, only water level change in the pond is recorded at the outlet. Outlet flows based on a change in the water level of the pond were calculated using the Bernoulli equation assuming a free jet at the outlet and negligible water velocity behind the dam. With terms appropriately rearranged to determine flow, the equation is

$$Q = \left(\frac{2gA\Delta z}{1 + \sum h_L} \right)^{1/2} \tag{1}$$


Figure 4. Outlet Pond Leveler

where Q = outlet flow, g = gravitational constant, A = cross-sectional area of outlet orifice, Δz = change in water level height between the pond and the riser orifice, and Σh_L = the sum of head losses attributable to pipe entrance, contraction, and the bend in the pipe. Head loss attributable to friction is considered negligible since the pipe is very short. Depth level data recorded by the automatic sampler at the outlet station reflect the height of water in the pond relative to the riser height. The depth sensor was mounted approximately 15.24 cm below the pipe orifice, therefore the minimum pond level could only be recorded at -15.24. Negative levels indicate pond level below riser orifice; "zero" level indicates water level at the riser orifice, but not flowing out; positive levels indicate sufficient level to cause outflow according to equation 1.

Water Balance Data

To determine the hydrologic budget, water balance data collected at the site included inflow and outflow measurements and precipitation. Data were logged continually from September 6 through October 27, 1997. Most of the data recorded represent 5-minute averages. Storm event data were logged at 1-minute intervals. For purposes of comparison, a more direct measurement of the change in storage of the wetland was also calculated strictly according to the change in water level recorded in the beaver pond, which is assumed to be uniform throughout the system. Because of the presence of standing water over most of the site, this seems to be a reasonable assumption. The initial level used for the change in storage calculation (discussed in equations 2 and 3) was taken as the level before the onset of rain, whereas the final level was considered as the pond level when all runoff and rain had ceased entering the wetland in the case of no outflow, or when the pond level once again reached the "zero" level in the case that outflow had occurred.

Climatic data including temperature, dew point, relative humidity, wind speed, sunshine hours, and Class A pan evaporation were obtained from the State Climatology Office at the University of Virginia in Charlottesville. Climatic data were recorded at a Class A weather station at Richmond WSO Airport, approximately 20 km from the site. Class A pan evaporation data were collected at the weather station at John Kerr Dam near the Virginia–North Carolina border. This is the closest weather station that collected Class A pan data. The data were used to estimate wetland *ET* for the growing season with the Penman's method, for the year with Thornthwaite's method, and for 2 months with Class A pan evaporation correlation. Data were reduced from hourly averages to daily averages. Monthly temperature averages were obtained directly for the remainder of the year not including the growing season for use in the Thornthwaite method.

RESULTS

Literature Review

In the most basic form, a hydrologic budget is simply a "black box" calculation balancing all inputs and outputs of water with the change in volume of water stored in the system. For a given period of time, Δt, discrete determination of storage change yields

$$\frac{\Delta S}{\Delta t} = P + Q_{si} + Q_{gwi} - Q_{so} - Q_{gwo} - ET \quad (2)$$

where P = precipitation, Q_{si} = surface inflow (including runoff and channel flow), Q_{gwi} = groundwater inflow, Q_{so} = surface outflow, Q_{gwo} = groundwater seepage, ET = evapotranspiration, and S = water storage of system. All terms are expressed in volume per time. For wetland conditions to exist, the sum of the inputs must be greater than the sum of the losses for most periods, thereby maintaining a positive value for the storage term. Consistent positive values for the storage term indicates potential for development of hydric soil conditions. In permanently flooded wetlands, $\Delta S/\Delta t = 0$ or is greater than zero for almost the entire growing season (Garbisch, 1994). In stormwater-supported wetlands, $\Delta S/\Delta t$ is often less than zero; therefore, it is in VDOT's best interest to evaluate whether the hydrology of a constructed wetland site meets federal requirements between storms.

Precipitation can be a significant source of water to wetlands where inputs are dominated by surface runoff. However, approximately 10 to 20 percent of precipitation is lost through interception by the vegetation and returned to the atmosphere through direct evaporation. If $P < 0.025$ cm, interception losses may be as high as 100 percent, and even when $P \approx 1$ cm, losses can still be as high as 40 percent (Garbisch, 1994; Viessman & Lewis, 1996). Viessman & Lewis reported interception losses between 14 and 60 percent for various grasses ranging in height up to approximately 1 m. During more severe storms, interception losses can be considered negligible. For the analysis presented in this report, 26 percent interception loss is assumed for storms that totaled less than 2.5 cm of rain. The loss coefficient (26%) reflects interception loss for mixed grass species varying in height up to approximately 1 m as reported by Viessman & Lewis. Precipitation that finally reaches an unsaturated ground surface often remains in the upper layers of the soil and is subsequently returned to the atmosphere through evaporation from bare soil or through plant transpiration within several hours of a storm event (Culler, Hanson, Myrick, Turner & Kipple, 1982).

Surface water inflows and outflows (Q_{si}, Q_{so}) account for water flowing into and out of systems via open channels or overland flow. Common forms of surface flow include streams, rivers, and highway drainage systems that convey stormwater runoff as in the case of many VDOT constructed wetlands. Natural and constructed wetlands supported solely by runoff are threatened by potentially limiting hydrologic conditions. The frequency, intensity, and duration of storms and the general hydrologic characteristics of a drainage area dictate the amount of water a wetland will receive as stormwater runoff (Garbisch, 1994).

Groundwater inflows and outflows (Q_{gwi}, Q_{gwo}) can be significant sources or losses in the case of natural systems; however, these terms can often be neglected in the water balance for constructed wetlands. Most artificial wetlands are built such that the underlying strata are compacted during construction or are designed with confining layers to prevent seepage, such as geomembrane liners. In either case, for most constructed wetlands, the permeability of the bottom layer is sufficiently reduced to minimize seepage (Hammer & Kadlec, 1986; Pierce, 1993). In general, subsurface contributions are often negligible (<0.01%) when there is above-ground flow (Hammer & Kadlec, 1986). Groundwater interactions were considered negligible for all cases in this analysis.

ET is the combined loss of water to the atmosphere attributable to direct evaporation from bare surfaces (including exposed soil surfaces and water intercepted by plants during precipitation) and transpiration by plants. The significance of water loss through *ET* should not be discounted as evidenced by estimates that place *ET* as the second largest term (quantitatively) in the global water budget, surpassed only by precipitation (Jensen, Burman & Allen, 1990). *ET* occurs as a result of an energy and water exchange in the root zone and near the earth's surface. Water loss is, therefore, a function of several parameters including atmospheric and climatic conditions and land surface characteristics such as topography and vegetative cover. Land surfaces and slopes affect fluxes of moisture and heat attributable to differences in water availability, variability of precipitation, surface temperature, and plant and soil parameters (Molders & Raabe, 1996). The influence of so many parameters renders direct measurement complex and expensive. A direct measurement device such as a lysimeter requires careful installation and calibration to simulate natural conditions in a spatially limited environment. The complexity and expense related to direct *ET* measurement by a lysimeter renders it beyond the scope of this project, but results of lysimeter studies can be found in Daniels et al. (1997). To estimate *ET* by more economical means, several estimation techniques have been developed that encompass a broad range of data intensity requirements.

Methods Selected to Estimate *ET*

Four methods were selected to estimate *ET*: (1) water balance equation, (2) Thornthwaite's method, (3) Penman's method, and (4) the Class A pan evaporation method.

The methods vary in data intensity and applicability. Further, several of the equations calculate *potential ET*, which is the rate at which *ET* would occur when the amount of available moisture exceeds the amount required by the soil and vegetation. If water stress is a factor, *actual ET* occurs at a rate less than the potential rate. Potential *ET,* therefore, represents the maximum rate at which water could be lost due to *ET*. The case for consideration of examples of maximum water loss has already been discussed, so no distinction is made between *potential ET* and *actual ET* in the remainder of this report.

Water Balance Equation

The water balance equation (equation 2) can be used to calculate *ET* with a few assumptions. When the time scale under consideration is short, such as the duration of a storm, *ET* losses are negligible compared to the amount of rainfall and surface flows. Therefore, in terms of volumes of water, the change in storage is equal to the sum of net precipitation (precipitation less interception loss) and surface inflows minus surface outflows. For systems supported by stormwater runoff only, the change in storage equals the change in water volume available for *ET* after a storm. Rearranging equation 2 calculates the volume of *ET* as a "residual" term in the water balance

$$ET = \frac{\Delta S}{\Delta t} + Q_{so} - Q_{si} - P_{net} \tag{3}$$

where now $P_{net} = P$ - Interception loss (when appropriate) and groundwater terms have been dropped from the equation. To address concerns of a potentially significant reduction of water storage in determining hydrologic characteristics of mitigated wetland sites supported only by stormwater runoff, it is important to consider the time after a storm before which the volume of water associated with the change in storage will be lost.

Thornthwaite's Method

Where site conditions or other factors prevent flow monitoring, estimating *ET* is possible using a variety of empirical equations that vary in data intensity requirements. Perhaps the simplest calculation of *ET* rates is by a temperature-dependent equation. Thornthwaite's method relies on mean temperature data and location latitude. The method requires calculation of the following series of equations, where U is the unadjusted potential *ET* expressed in centimeters per month

$$i = \left(\frac{t}{5}\right)^{1.514} \tag{4}$$

$$I = \sum_{1}^{12} i \tag{5}$$

$$U = 1.6\left(10\frac{t}{I}\right)^{a} \tag{6}$$

$$a = \left(6.75\times10^{-7}\right)I^{3} - \left(7.71\times10^{-5}\right)I^{2} + 0.01792I + 0.49239 \tag{7}$$

where i and I are termed heat index and monthly heat index, respectively, t = mean monthly temperature in °C, U = unadjusted potential *ET* (cm/month), and a = coefficient (Devi, 1992; Pierce, 1993). Depending on the temperature, the unadjusted potential *ET* rate (U) is adjusted for location and time of year using tabulated correction factors published in the literature, such as Pierce (1993). According to the method, the unadjusted potential rate does not require correction when mean temperatures exceed 26.5 °C. However, as mean monthly temperatures drop below 26.5 °C, the diverging relationship between temperature and potential *ET* becomes more pronounced and the application of adjustment factors has a more significant influence on the estimation (Devi, 1992; Pierce, 1993).

Penman's Method

The simplicity of Thornthwaite's method renders its application appealing; however, for study periods shorter than 1 year, the technique is not recommended. Penman (1948) developed an equation that combined theories of mass transfer and energy budgets. The complexity of Penman's equation accounts for several climatic conditions, sink strength (i.e., the ability of the atmosphere to absorb moisture), and potential effects of the surrounding microclimate (i.e., advection of energy into the system) in its computation of daily *ET* rates. The Penman equation is of the form

$$ET = \frac{\frac{\Delta}{\gamma}\left[R(1-r)\left(a+b\frac{n}{N}\right)-\sigma T_a^4\left(0.56-0.092\sqrt{e_d}\right)\left(0.1+0.9\frac{n}{N}\right)\right]+0.35\left(e_a-e_d\right)\left(1+0.0098u\right)}{\frac{\Delta}{\gamma}+1} \quad (8)$$

where ET = potential evapotranspiration (mm H_2O evaporated per day), Δ = slope of the saturation vapor pressure of air curve (mm Hg $^oF^{-1}$) (not to be confused with Δ from equations 1 and 2), $\gamma = 0.27$ and is the constant of wet and dry bulb hygrometer equation, R = mean monthly extraterrestrial radiation (mm H_2O evaporated per day), r = estimated percentage of reflecting surface (also called albedo), n/N = ratio of actual to possible sunshine hours per day, σ = Stefan-Boltzman constant, T_a = air temperature (^oF), e_a, e_d = saturation vapor pressure at air and dew point temperature, respectively (mm Hg), u = wind speed (mpd, usually measured at a height of 2 m above the ground), and a and b are location-dependent constants, suggested as $a = 0.22$ and $b = 0.54$ for Virginia (Penman, 1948). Values of R and the quantity σT_a^4 are found in tabular form and are expressed in mm H_2O evaporated per day (Viessman & Lewis, 1996). The slope of the saturation vapor pressure curve (Δ) can be either determined graphically or estimated by the following equation after Raudkivi (1979)

$$\Delta = \frac{4.098 e_{sat}}{(237.3+T)^2} \quad (9)$$

where Δ is given in kPa $^oC^{-1}$, e_{sat} is in kPa, and T is in ^oC.

The Penman method is fairly data intensive, but there is general agreement in the literature that it is the most accurate technique, particularly for estimates of daily ET (Hargreaves, 1994; Jensen et al., 1990). When averaged over the course of a year, the Penman and Thornthwaite estimates are reported to be relatively close. Seasonally, overestimation occurs during winter months for the Penman method and during summer months for the Thornthwaite method.

Class A Pan Evaporation Method

It has been suggested that wetland ET can be estimated over the entire growing season accurately enough with lake evaporation as related to Class A evaporation pan data (Ingram, 1983; Kadlec, 1983; Mitsch & Gosselink, 1986; NCHRP, 1997). This estimate may not be as accurate for periods shorter than an entire growing season because of the short-term effects of vegetation (Mitsch & Gosselink, 1986). Class A evaporation pan data are collected by most National Weather Service Class A weather stations. If ET is assumed to approximate lake evaporation, then

$$ET = 0.7 \times \text{Class A Pan Evaporation} \quad (10)$$

Computing the Hydrologic Budget

Water Balance Equation

Four storms were recorded during the period September 6 through October 27, 1997. Their duration ranged from 1 day to approximately 3 days, with the exception of the October 14 storm. Storms ranged from 1.0 to 13.7 cm in total precipitation and were characteristic of a relatively dry late summer and early fall in Virginia in 1997. Calculation of water balances according to equation 2 includes the period from when rain events began to when inflows or outflow ceased, whichever was longer. Table 1 shows the water balance. Figure 5 shows agreement between change in storage according to equation 1 and according to calculation by change in the pre- and post-storm pond water level.

Table 1. Rte. 288 Mitigated Wetland Water Balance (cm water over entire wetland)

Storm	Inlet 1	Inlet 2	Inlet 3	Net Precipitation	Outlet	Change in Storage
9/10/97	0.69	0.00	0.04	0.45[a]	0.00	1.18
9/28/97	0.65	0.00	0.04	1.35[a]	0.00	2.04
10/14/97	3.33	0.00	0.22	13.66	0.00	17.21
10/24/97	2.71	0.00	0.10	12.95	8.20	7.56[b]

[a] Net precipitation = Precipitation - 26% interception loss.

[b] Adjusted by back-calculation using Bernoulli equation to calculate complete outflow.

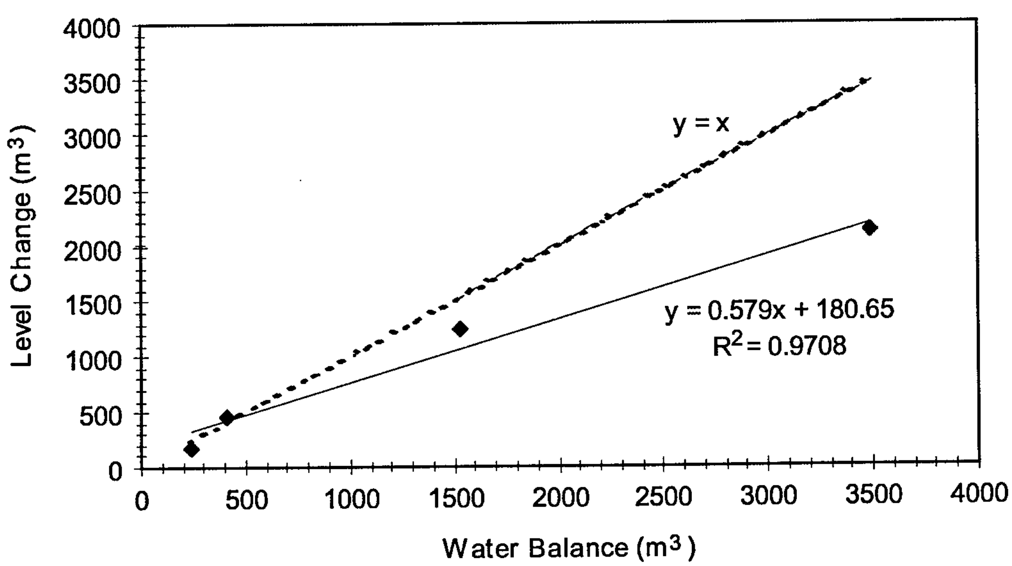

Figure 5. Agreement of Storage Calculations Between Water Balance and Level Change

Penman's Method

Hourly data obtained from the State Climatology Office were reduced to daily averages when appropriate, with the exception of sunshine data. Figure 6 shows *ET* estimates for the growing season calculated by equations 8 and 9.

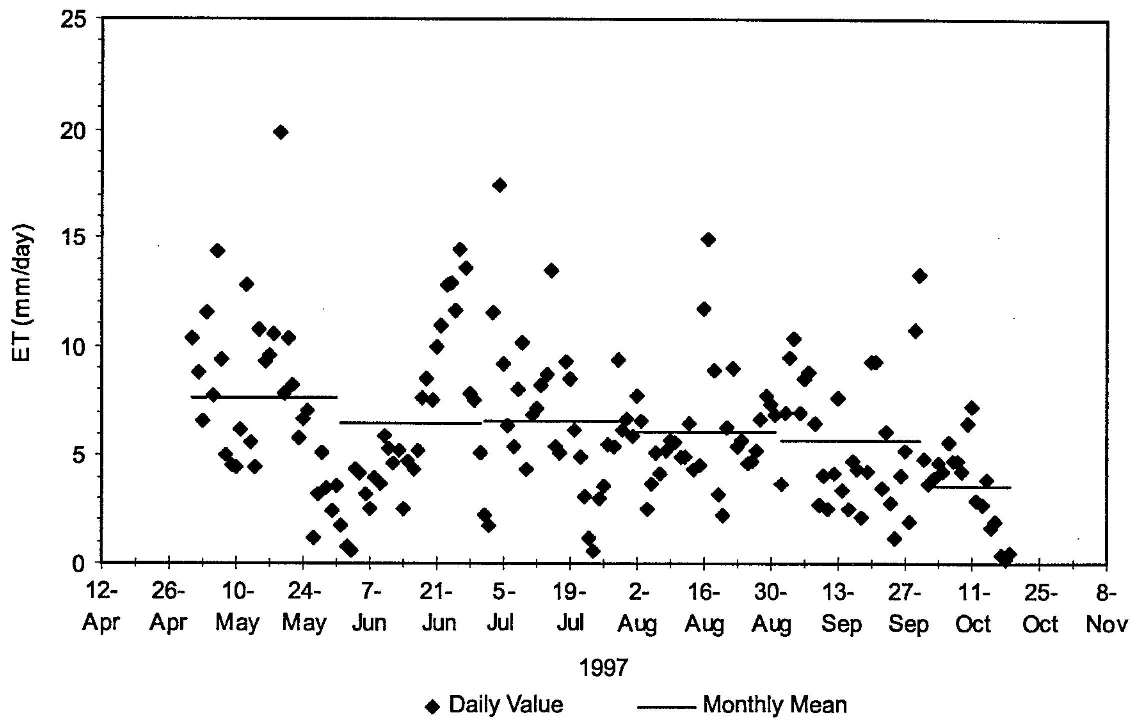

Figure 6. Daily ET Estimates by Penman Method for Growing Season

Thornthwaite's Method

Figure 7 presents monthly *ET* estimates for 1997 calculated with equations 4 through 7. The figure also presents estimates calculated using 1995, 1996, and 30-year normal average monthly temperature data.

Comparison of Methods

Differences between the Penman daily *ET* and that estimated using the water balance equation are shown in Figure 8. Figure 9 presents the growing season Penman and Class A pan evaporation daily *ET* estimates. Table 2 shows monthly *ET* estimates calculated by the Penman, Class A pan evaporation, and Thornthwaite methods. Table 3 compares the time passed after each storm before the quantity of wetland storage increase is reduced to pre-storm levels attributable to *ET* losses according to each method and assuming no rainfall in the calculated period.

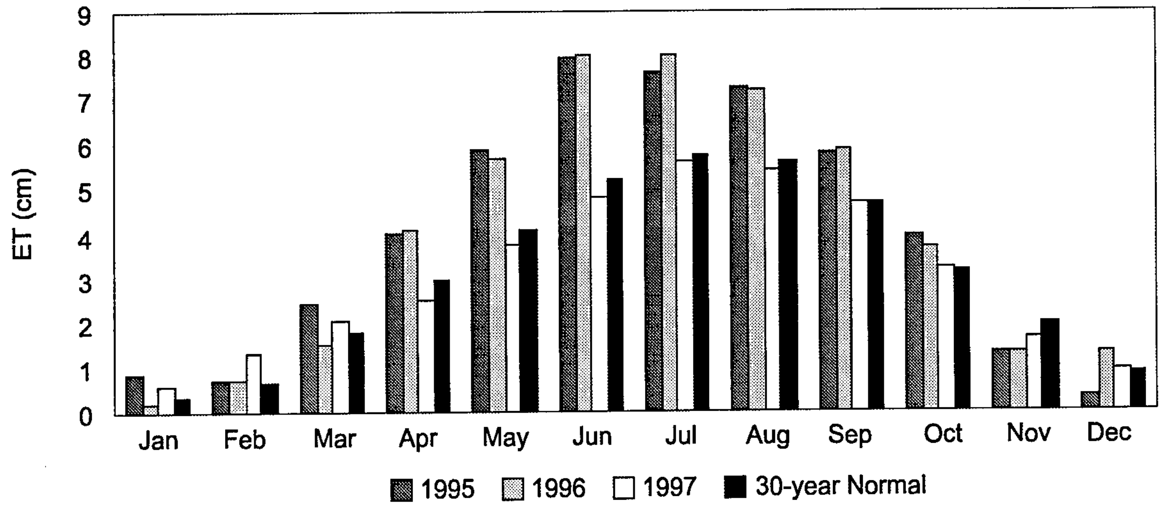

Figure 7. Monthly ET Estimates by Thornthwaite Method

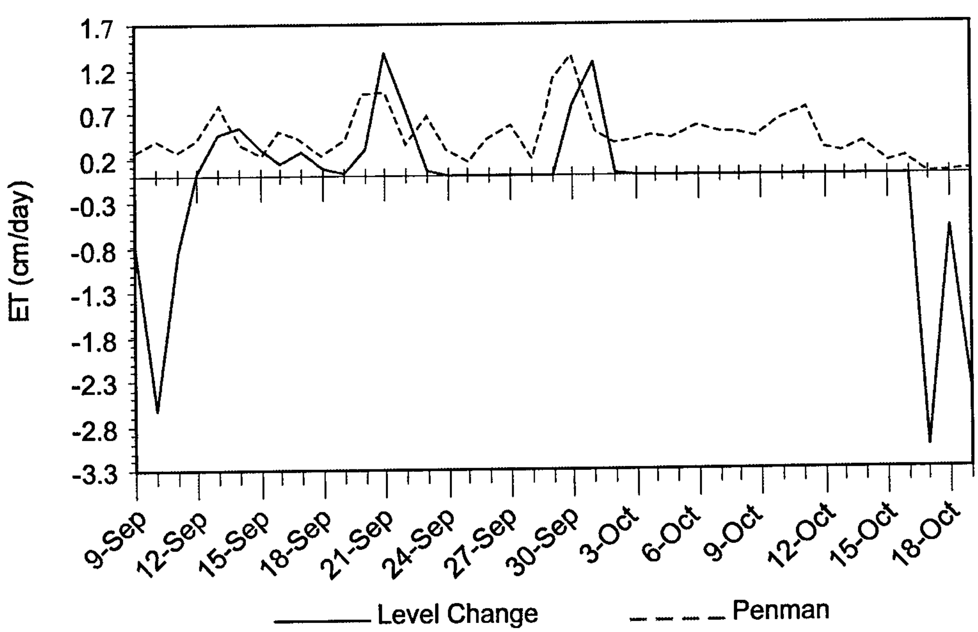

Figure 8. Daily Penman and Level Change ET Estimates

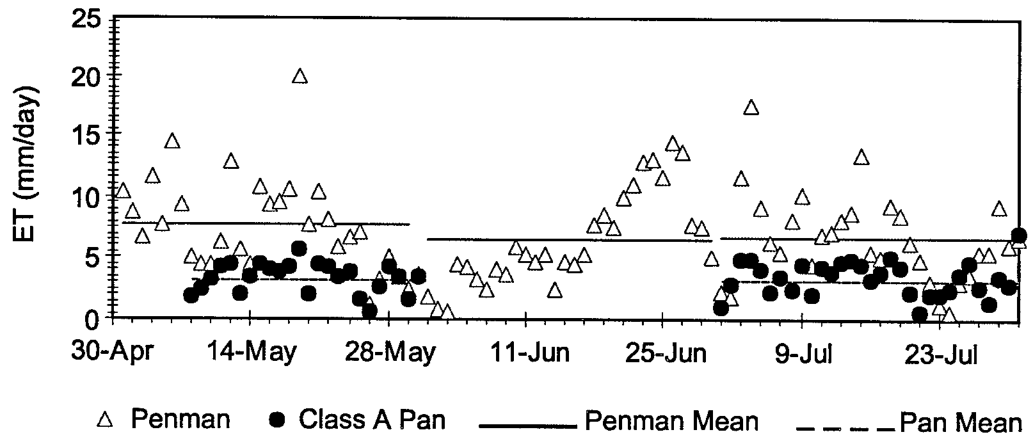

Figure 9. Penman Method and Class A Pan Daily ET Estimates

Table 2. Monthly Evapotranspiration Rate Estimates (cm/month)

Month	Penman[a]	Class A Pan	Thornthwaite[b]	Thornthwaite[c]
May	23.7	10.29	3.79	4.13
June	19.36	---	4.82	4.20
July	20.53	10.35	4.66	4.76
August	18.84	---	4.39	4.59
September	17.11	---	4.68	4.47

[a]Determined by sum of daily values for individual months.
[b]Calculated with 1997 mean monthly temperatures.
[c]Calculated with 30-year normal monthly mean temperatures.

Table 3. Time Required for Post-Storm Loss of Storage Gains by Four Evapotranspiration Estimates (days)

Storm	Thornthwaite[a]	Penman[b]	Penman[c]	Level Change[d]
9/10/97	7.57	2.07	3	4
9/28/97	13.08	3.57	3	4
10/14/97	166.10	4.78	---	---
10/24/97	72.96	2.09	---	---

[a]Estimated from monthly rate.
[b]Estimated from average monthly rate.
[c]Estimated from cumulative daily totals.
[d]Estimated directly from cumulative level change at outlet.

DISCUSSION

Water Balance Method

The October 14 storm represents the period October 14 at 20:00 to October 23 at 06:00. This appears to be an unusually long storm. The storm was made up of three distinct intervals of rain, but significant amounts of runoff continually entered the wetland throughout the entire 9 days. Precipitation occurred on 4 days and the time between events was short enough to consider *ET* losses negligible during these periods. For all storm events, *ET* was considered negligible compared to the amount of water entering or exiting the system from all components of the water balance.

During the periods September 10 to September 15 and September 29 to October 6, the automatic sampler at inlet 2 was either not turned on or not functioning properly. Of the periods missing data, no precipitation or inflow was recorded at any other stations from noon September 12 to September 15 or from September 26 to October 6. It is, therefore, assumed that there was no inflow at inlet 2 either. The concrete pipe was often dry during site visits after storms during the summer of 1997, which supports the assumption of no inflow. For the September 10 to September 12 storm, inflow was possible through inlet 2, but two reasons suggest that neglecting any possible inflow is acceptable. No outflow was recorded for this storm, suggesting that even if inlet 2 contributed to the change in storage, it was not a sufficient amount of water to raise the pond level enough to create outflow. If inlet 2 had conveyed water to the wetland, the calculated storage term would increase. Neglecting runoff inflow via inlet 2, therefore, potentially underestimates the change in storage and contributes to the analysis of hydrology under minimum conditions.

Further, the agreement between the change in storage as calculated by equation 2 and by pond level change is fairly good, as shown by Figure 5. The storage values are plotted against each other. Statistical analysis of the results yields a correlation value of 0.985, which indicates a strong positive linear relationship between water balance and level change storage calculations. A straight line drawn between data points with a slope equal to 1 and an intercept of 0 would indicate 100 percent agreement between calculations. Actual linear regression yields

$$\Delta S_{LC} = 0.579\Delta S_{WB} + 180.65 \tag{11}$$

where ΔS_{LC} = volume of storage change according to level change method (m^3) and ΔS_{WB} = volume of storage change according to water balance method (m^3). The goodness of fit of the regression model is measured by $R^2 = 0.9708$, which indicates that actual data points lie within 97.08 percent of the predicted values. The difference between the idealized slope (1.0) and the regression slope (0.579) results in water balance storage change estimates approximately 40 percent higher than level change estimates. The volume associated with the intercept is equivalent to 0.89 cm of water over the entire wetland. Deviations from perfect agreement suggest possible errors in the measurement of flows and/or precipitation. Measurements are limited by equipment sensitivity. Error is inherent in all measurement, but the level change estimate requires only one measurement, whereas the water balance method requires quantification of several parameters and, therefore, has a larger margin for error. Overall, the regression equation indicates that the water balance method predicts higher values for the change in storage than the level change estimates, but by a predictable amount. Prediction of storage change by the water balance method, therefore, serves as an acceptable substitution for level change for the analyses presented in this report. Returning to the discussion of the water balance, the predictable relationship between the two methods of change in storage calculation suggests that any contribution by inlet 2 would not have a significant effect on the overall water balance.

Data collection ceased at noon on October 27, 1997; however, water was still flowing out of the wetland at this time. To determine the total water lost via the outlet for the October 24 storm, back calculation was performed using the Bernoulli equation (equation 1) rearranged to predict level change and resulting flow, until the pond level was reduced to the zero level.

The summer of 1997 was fairly dry. Since the mitigation site is supported solely by stormwater runoff, 1997 may not be a representative year for the site's long-term water balance; however, it does serve as a good example of environmental "worst-case scenario" conditions. *ET* was most likely a significant factor in water loss during the growing season. For example, the wetland water level was indeterminate for most of the time from September 8 to September 9, September 22 to September 27, and September 30 to October 17. Data indicate that the pond level was at the minimum detectable limit, with the exception of the period from 16:00 October 13 to 14:00 October 17 when no data were recorded at the outlet station. If *ET* occurred during these intervals, estimation by level change is not possible. The subsequent underestimation of *ET* results in overestimation of the amount of storage increase according to the water balance. The assumption is supported by the lack of outflow during the October 14 storm, even though the storm lasted approximately 9 days and precipitation totaled almost 14.0 cm. Although frequent site visits (once or twice per week) showed that most of the wetland was still saturated, the pond level was often significantly below the outlet riser orifice between storm events.

Penman's Method

Daily values for Penman *ET* estimates are scattered significantly about the mean monthly value, where monthly means are taken as the sum of daily *ET* then divided by the number of days in the month. As daily estimates are summed to produce total *ET* for a given period, the estimate approaches the monthly mean. A monthly total for October was not available because of a lack of data. Daily values were determined from May 1 to October 19, 1997.

The intensity of data requirements to calculate *ET* by Penman's method led to complications. Sunshine data for 1997 are not yet available. Values used for the ratio *n/N* are the 30-year normal monthly averages. The results do not seem to be significantly affected by the value of the ratio. For comparison, Penman *ET* was also calculated using 1995 monthly averages for sunshine data. The relative percent difference (rpd) for daily values ranged from 0 to 0.04 percent. The difference is small enough to suggest that the value of the ratio does not have a significant effect on the estimates. Likewise, rpd between sunshine data for 1995 compared to the 30-year normal means is 11.56 percent, which implies that the variation in monthly sunshine ratios between years is not too significant. Further, Figure 10 reveals that the 30-year normal average monthly temperatures consistently lie above the minimum and below the maximum for the growing season. This suggests that the normal values accurately represent the conditions for the given period. Since temperature is a function of sunshine, it seems that this reasoning also applies to the sunshine data. Therefore, the substitution of the 30-year normal monthly averages for daily 1997 values is acceptable.

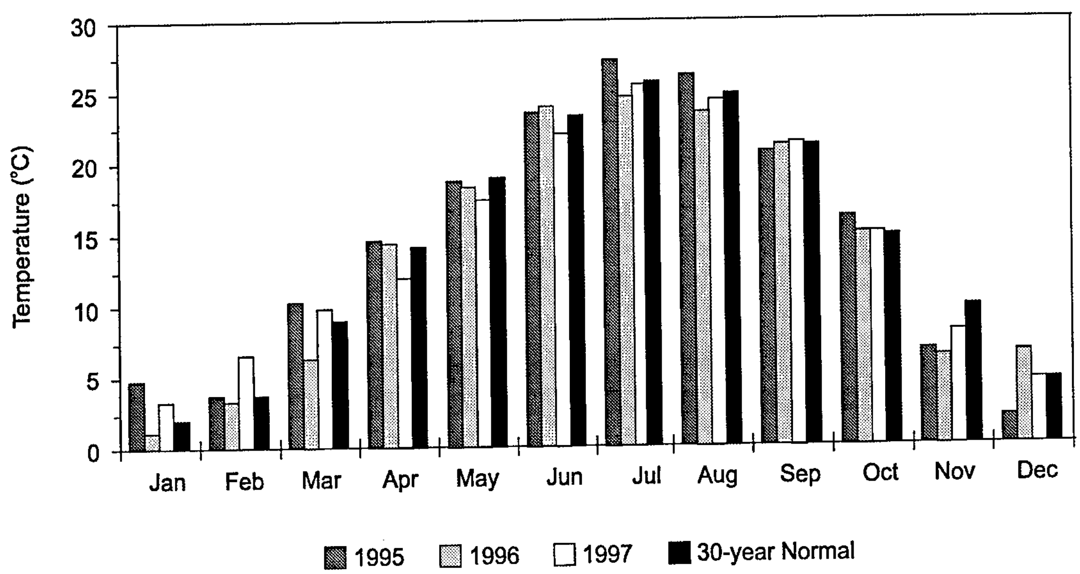

Figure 10. Average Monthly Temperatures at Richmond WSO Airport

Determining albedo (the fraction of incoming radiation reflected back to the atmosphere by a surface) was somewhat difficult. Wetland vegetation is heterogeneous, as evidenced in Figure 2. Although no studies were found in the literature designed specifically to determine wetland albedo, several sources suggest that $r = 0.23$ adequately estimates wetland reflectance (Devi, 1992; Garbisch, 1994; Penman, 1948). A summary of albedo for specific wetland species presented in Ingram (1993) suggests that $r = 0.22$ for cattails and $r = 0.16$-0.22 for Sphangum moss, two commonly found wetland species. A unique value for albedo for the entire growing season also seems to oversimplify actual conditions.

Temperature is a localized climatic phenomenon. Significant variations in temperature (and, therefore, dew point temperature, relative humidity, saturation pressures, and Δ) may occur between the location of the data recording and the actual site. Differences may be especially pronounced during summer months when isolated thunderstorms are common. VDOT maintains a roadside monitoring program that records various road surface data including temperature and the presence of precipitation at several locations around Virginia; however, the monitoring station closest to the Rte. 288 mitigation site (which would have been closer than the Richmond airport) was not operating during the period of this study or for the remainder of the growing season.

Thornthwaite's Method

Potential improvements in the application of Thornthwaite's method for estimating *ET* from the Rte. 288 mitigation site would result if temperature measurements had been made on site. The effect of temperature variation on Thornthwaite *ET* estimates is demonstrated by comparing estimates for 1995, 1996, 1997, and the 30-year normal monthly average *ET*. Figure 10 shows very little variation in average temperatures for any given month. However, because Thornthwaite's Method is an exponential equation, even small temperature differences result in significant variation in *ET* estimation, as shown in figure 7.

Correction factors are tabulated according to month and latitude in ten degree increments. Correction factors applied in the current calculations were obtained by graphical interpolation for site location (approximately 37°N latitude).

Although Thornthwaite's method may be attractive because of the simplicity of calculation, the equation does not account for any of the unique conditions that distinguish wetlands from other types of terrestrial or aquatic systems and may have an effect on actual *ET* loss.

Class A Pan Evaporation Method

Approximation of wetland *ET* using Class A pan evaporation for 1997 is limited by several factors. Class A pan data were not available for the study period, rendering direct comparison to *ET* estimates by level change impossible. Further, data were collected at a weather station located approximately 130 km from the site. Adjustment of Class A pan evaporation with a reduction coefficient is recommended for pan data collected at an adjacent site. For similar reasons as discussed in the previous section regarding localized climatic conditions, pan data may not accurately reflect conditions near the site.

Comparison of Methods

Penman Daily ET and Estimation by Daily Changes in Pond Level

Pond level change not associated with storm events represents *ET* loss according to the water balance equation (equations 2 and 3). Neglecting days associated with storm events (when level change is positive) and when the pond level was below the detectable minimum for extended periods, the Penman method produces *ET* estimates significantly greater than estimation by level change. The average rpd between the estimates for the 15 comparable values was 99.42 percent. Although significant variations occur on a daily basis between methods, the differences become less pronounced as total *ET* water loss is obtained by summing daily values over time. Although the Penman method estimates are consistently higher than the level change estimates, maximum *ET* rates as predicted by level change estimates are accurately reflected.

The Penman method predicts *ET* even during storm events. The equation accounts for the strength of the atmosphere as a sink for moisture by including parameters such as relative humidity and vapor pressure. Water loss from the system to the atmosphere is potentially physically possible as long as the atmosphere is less than 100 percent saturated. On a small spatial scale, such as the Rte. 288 site, the assumption that *ET* losses during storm events compared to the volume of water entering the system is acceptable. However, for larger wetland systems supported only by stormwater runoff, the assumption may not be valid, depending on specific site characteristics.

Results of a water budget study for a 46.7-ha marsh mitigation site in south central Virginia cited by Pierce (1993) indicated a mean growing season *ET* loss of 12.2 cm/month, determined by the water balance methods. The mean growing season *ET* loss estimated by Penman's method for the Rte. 288 site was 19.9 cm/month. Although rpd between means is approximately 48 percent, differences can be attributed in part to the extreme difference in size of the wetlands. Advective effects of the surrounding microclimate will have a more pronounced effect on the water budget of the Rte. 288 mitigation site because of its smaller size (2.02 ha) compared to the mitigation site discussed by Pierce. Road surface temperatures are generally fairly high in the summer months, thereby creating potentially unstable atmospheric conditions and further enhancing advection of energy to the wetland. Since the Rte. 288 site is in the median of a highway, elevated temperatures immediately surrounding the site might increase *ET*. High *ET* rates reported for a tank study in a small wetland in Idaho were attributed to advection, where *ET* was measured as the amount of water required to maintain a tank water level at a specified height (Linacre, 1976). Results of an as yet unpublished study by Allen (1998) reinforces the influence of advection on *ET* for small wetland sites. Another tank study by Young and Blaney as presented by Linacre, which was designed to investigate effects of vegetation on wetland *ET*, reported differences in *ET* rates for July and August ranging from 37 to 75 cm/month, depending on the type of vegetation. The wide variety of vegetation species present at the Rte. 288 mitigation site, therefore, might also factor into the differences between the findings of this study and those presented in the literature.

Monthly ET Estimates Calculated by Penman, Class A Pan Evaporation, and Thornthwaite Methods

Comparison of monthly *ET* estimates by the empirical methods presented in this report indicate that when applied to water balance calculations, the Penman method will produce the most conservative estimation. In other words, the method will predict the worst case scenario as far as maximum *ET* is concerned and, therefore, underpredicts the actual volume of water in the wetland.

Growing Season Penman and Class A Pan Evaporation Methods

Wetland studies that estimate *ET* loss by reduction of Class A pan evaporation data suggest that values should not be used for periods shorter than 1 month, and for more accurate estimates, for periods less than an entire growing season. Monthly Penman *ET* for the months of the growing season serves as an acceptable baseline comparison for Class A pan evaporation data results when level change data were not available. (As discussed previously, as the duration of comparison between Penman and level change *ET* estimates increases, Penman *ET* approximates level change *ET* fairly well.) Class A pan evaporation and Penman estimates differ by 71.32 percent rpd. Back calculation for a more accurate coefficient to apply to Class A pan evaporation to reflect conditions at the Rte. 288 site reveals that for May, the coefficient should be 1.61, and for July, the coefficient should be 1.39. A value of the coefficient greater than 1.0 suggests that transpiration by plants has a greater effect on storage volume than prevention of *ET* attributable to shading by the vegetation.

Reduction to Pre-storm Storage Volume Attributable to ET

The hydrologic conditions between storm events for the Rte. 288 mitigation site, as well as any other VDOT constructed wetland supported by stormwater runoff, are of particular interest when considering whether the site meets COE mitigation site hydrologic requirements. Interstorm water levels are also important in design considerations when a wetland is designated as a BMP for controlling water quality. A constructed site may be sized such that all runoff is contained indefinitely and the majority of water gained is lost by *ET*, i.e., zero direct discharge of the system. In terms of water quality benefits, this type of design prevents any pollutants from reaching downstream environments but causes increased concentrations of pollutants within the wetland system itself. In such a case, an event in volumetric excess of the design storm may cause concentrated quantities of pollutants to wash out of the wetland, thereby potentially causing harm downstream. Conversely, nutrient-rich wetlands will produce diverse and dense vegetation.

Table 3 shows that of the methods presented, the accuracy of both Penman estimates is supported by the level change estimate. The general trend of the Penman estimates closely mimics the level change estimates as shown in Figure 8, particularly during periods of maximum water loss, indicated by the peaks on the graph. Penman monthly average and daily sums are presented to demonstrate the effect of averaging daily values, as discussed previously. Conversely, the Thornthwaite estimate underpredicts water loss.

CONCLUSIONS

- Of the empirical relationships investigated during this study, the Penman method calculates the highest *ET* rates and produces the most conservative estimates of the water balance. Therefore, the method predicts the most limiting hydrologic conditions for a constructed wetland. Although the quantity of water lost by *ET* according to the Penman method is consistently higher than estimates given by level change, the method accurately demonstrates periods of maximum water loss.

- Estimation of wetland *ET* by relating it to Class A pan evaporation with a coefficient of 0.7 as recommended in the literature more closely represents the worst case scenario of maximum water loss attributable to *ET* than does the Thornthwaite method. However, the results are unreliable given the distance between the mitigation site and the weather station.

- Monthly *ET* estimation using the Thornthwaite method underpredicts water loss after storm events during September and October and, therefore, overestimates the amount of water in the system. These findings are supported by the preliminary results of Daniels et al. (1997).

- On-site climatic data collection, or even climatic conditions recorded by VDOT's roadside monitoring system, may have improved the accuracy of the estimation techniques, especially the calculations using the Thornthwaite method.

- The time scale for *ET* estimation is a significant factor when comparing various methods. Extreme variations in daily estimates become less pronounced when determining total *ET* by summation as the length of the period increases. This is especially true for application of the Penman method.

- The assumption that *ET* loss during storm events can be considered negligible may not hold for large wetland sites. All of the *ET* estimation techniques based on climatic and meteorological data presented in this paper predict *ET* losses even during storm events. For large wetland sites supported only by stormwater runoff, *ET* loss can be significant depending on the volumes of water entering the wetland. For small wetlands with comparatively large drainage areas, *ET* loss during storm events can be considered negligible.

- Hydrologic conditions of mitigated wetlands supported only by stormwater runoff are significantly affected by *ET* losses between storm events. The magnitude of impact depends on the frequency, duration, and intensity of storm events; climatic conditions; and site characteristics such as size and location within the landscape.

- The prediction of *ET* loss can be used as an aid in designing a constructed wetland depending on the specified use of the wetland (e.g., mitigation site as a water quality BMP).

RECOMMENDATIONS

1. In designing constructed wetlands supported only by stormwater runoff, consider the frequency, duration, and intensity of local storm events and the potential effect of *ET* losses on the hydrology of the site between storm events, particularly if the mitigation site is also designed as a BMP.

2. If more direct measurement of *ET* is desirable than estimation by empirical equations, calculate *ET* either by measuring the standing water level change between storm events or by quantifying all inflows and outflows to the system if site conditions render it feasible.

3. If flow monitoring or water level change monitoring is not feasible, consider *ET* estimation by the Penman method for the most accurate results.

4. Unless a Class A weather station that collects pan evaporation data is only a short distance from a mitigation site, do not estimate *ET* by applying a coefficient to pan data. However, the low cost and relative ease of this type of estimate suggest that further study of the method is warranted.

5. Use Thornthwaite's method for predicting wetland *ET* rates only when data for a more conservative estimator, such as the Penman method, are not available. Interpretation of results obtained by Thornthwaite method should include the concerns expressed in this report.

6. Whenever possible, ensure that hydrologic monitoring of VDOT constructed wetlands includes equipment to monitor and record climatic conditions on site. Climatic data such as temperature, relative humidity, and sunshine hours collected as close to the site as possible would provide the most accurate estimation of *ET* rates by empirical equations such as those presented in this report.

7. Use the Penman method to estimate maximum water loss. The method renders the most conservative design approach in terms of ensuring adequate water supply to maintain wetland hydrologic conditions.

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